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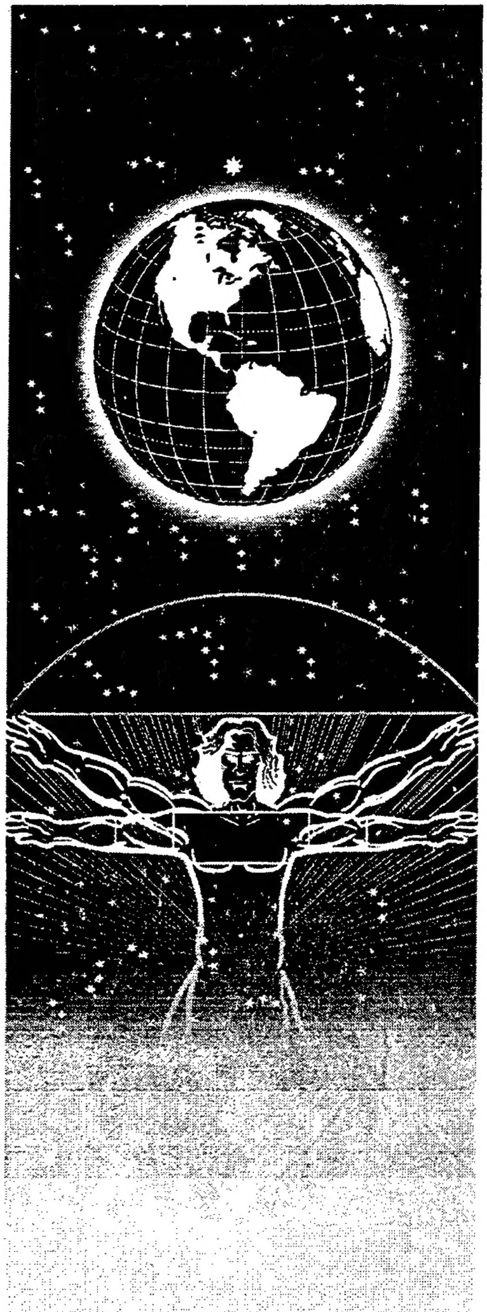

UNITED STATES AIR FORCE ARMSTRONG LABORATORY

Estimating Differences in the Cost of Groundwater Treatment of Trichloroethylene Based on Different Cleanup Goals

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13. ABSTRACT *(Maximum 200 words)*
The Department of Defense (DOD) is working with the US Environmental Protection Agency (EPA) to develop a health-based groundwater (GW) cleanup standard for trichloroethylene (TCE). Reevaluation of the health risk of TCE exposure may provide sufficient evidence for EPA program offices (such as the Office of Water) to review and perhaps revise the Drinking Water Standard for TCE. This paper will describe some of the issues related to the cost of remediating TCE contaminated GW as they pertain to alternate TCE cleanup levels.

An initial analytical basis for discussing the cost implications of using a TCE cleanup level in GW that is less stringent than the current level is provided. The paper discusses how cost estimates for the cleanup of TCE contaminated GW, based on modeling data, were developed for aquifers of different sizes using the current 5 ppb cleanup level and alternate cleanup levels of 50 and 100 ppb. Three retardation coeffiecients were used to simulate the effect of varying degrees of "stickiness" in the aquifer. Information derived from GW modeling was used to generate remedial cost estimates using the RACER System. An estimated mean cost for all outcomes was also developed. A comparison of the different mean costs for each cleanup level is made.

The model estimates that the DOD could avoid $442M if the MCL for TCE were raised to 100 ppb, a value not inconsistent with published literature. This is most likely a very conservative estimate of cost avoidance based on assumptions of the model. The cost avoidances associated with the acceptance of a scientifically based MCL would be significant to the DOD.

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ESTIMATING DIFFERENCES IN THE COST OF GROUNDWATER TREATMENTOF TRICHLOROETHYLENE BASED ON DIFFERENT CLEANUP GOALS

EXECUTIVE SUMMARY

Objective

This report discusses potential cost avoidance associated with less stringent cleanup endpoints for the remediation of trichloroethylene (TCE) as part of the Department of Defense's (DOD) work with the US Environmental Protection Agency (EPA) in developing a new health based standard for TCE.

Background

Reevaluation of the health risk of TCE exposure may provide sufficient evidence for US EPA program offices (such as the Office of Drinking Water) to review and revise their current, policy based, drinking water standard (the maximum contaminant level [MCL]) for TCE to a scientifically based standard. This paper will help clarify some of the issues related to the cost of removing TCE from the groundwater as they pertain to alternate TCE cleanup levels. An initial analytical basis for discussing the cost implications of using a TCE cleanup level in groundwater that is less stringent than the current level is provided. The paper discusses how cost estimates for the cleanup of TCE contaminated groundwater, based on modeling data, were developed for aquifers of three different sizes using the current 5 ppb cleanup level (or endpoint) and alternative cleanup levels of 50 ppb and 100 ppb. In addition, three retardation coefficients were used to simulate the effect of varying degrees of "stickiness" in the aquifer. Information derived from the groundwater modeling was used to generate remedial cost estimates using the Remedial Action Cost Engineering and Requirements (RACER) System. The same cleanup approach was used for each case. Costs for each case were estimated based on the various cleanup levels and retardation characteristics. An estimated mean cost for all outcomes also was developed. A comparison of the different mean costs for each cleanup level is made. The paper then discusses the potential effects of these changes on the overall cost to the Department of Defense (DOD) for TCE cleanup.

Conclusion

The major conclusion of this report is that significant costs can be avoided by making the current MCL for TCE less stringent by increasing it from 5 ppb to 100 ppb. The reported cost avoidance of $442 million is an extremely conservative estimate because of the approach used in developing modeling parameters for the groundwater model.

The overall percentage decrease in cost using a 50 ppb MCL is 19 percent. A 100 ppb MCL yields an average percentage decrease of 28 percent. Conservative assumptions used in this example (removal / containment of the source, size of plumes, initial maximum contaminant concentration of 200 ppb) will act to lower the actual cost avoidance. Using more realistic model parameters and assumptions would yield even larger cost avoidances. A proposal regarding additional work to refine the findings in this report is made.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) currently requires a groundwater cleanup concentration level (the maximum contaminant level [MCL]) of 5 parts per billion (ppb) for trichloroethylene (TCE). The MCL is a conservative regulatory standard based on an EPA cancer classification of B2 (probable human carcinogen) and economic and technical feasibility to detect TCE. Remediating groundwater to the MCL is an extremely difficult technical task that significantly increases the overall cost of cleanup. This paper discusses the effect of potential alternative cleanup levels for TCE on the cost of remediation of groundwater.

The Department of Defense (DOD) is working with EPA to establish a new health risk assessment for TCE. This paper will help clarify some of the issues related to the cost of removing TCE from the groundwater. This paper provides an initial analytical basis for discussing the cost implications of using a TCE cleanup level in groundwater that is less stringent than the current level. Furthermore, the paper discusses cost estimates for the cleanup of TCE contaminated groundwater based on modeling data provided for aquifers of three different sizes to allow a direct comparison of costs among aquifers and cleanup levels and discusses potential changes in the total cost of cleanup based on a mean of all costs. The same cleanup approach was used for each case. Costs for each case were estimated based on the various cleanup levels and carbon adsorption coefficient characteristics. An estimated mean cost for all outcomes also was developed. A comparison of the different mean costs for each cleanup level is made. The paper then discusses the potential effects of these changes on the overall cost to the DOD for TCE cleanup. This paper does not attempt to provide final answers, but is intended rather to prompt additional questions and discussion.

The first section of this paper presents a brief introduction to the paper's overall purpose. The next section presents background information about TCE in the environment; it briefly discusses EPA's rationale for requiring cleanup of groundwater to 5 ppb and provides background information on the behavior of TCE in the environment. The next section of the paper discusses the approach used in developing the parameters for the groundwater models and the parameters used in estimating the costs. The last section presents the results and discusses the potential cost

savings associated with a change in the groundwater cleanup requirement from 5 ppb to 50 ppb or 100 ppb.

Background On TCE In The Environment

This section presents background information about TCE and its behavior in the environment. It briefly discusses why the National Primary Drinking Water Standards (NPDWS) first listed TCE and describes behavior of TCE in the environment. Readers who wish a more detailed understanding of either issue will find pertinent documents in the References.

EPA's Rationale For Listing TCE

The toxicology of TCE has been studied since the early 1960s. The U.S. government published a study of occupational exposure to TCE in 1973 (Aviado *et al.* 1976). Aviado *et al.* (1976) reported that fluorocarbon *(sic)* propellants such as TCE initially were thought to be biologically inert, but that, by 1976, there was definite evidence of their toxicity. Early toxicological studies focused on toxicity resulting from inhalation; later studies focused on toxicity resulting from ingestion (Aviado *et al.* 1976; ATSDR 1989).

EPA regulates groundwater used for drinking by imposing maximum contaminant levels (MCL) for individual constituents. MCLs are not based strictly on the protection of human health, but also consider the economic and technical feasibility of detecting a particular chemical concentration (cleanup goal). In 1985, EPA published its intention to include an MCL for TCE in the NPDWS that would be finalized in 1987. The rationale provided for listing TCE was based on its widespread use, primarily as a degreaser, in industry; ability to leach into groundwater from sources such as landfills; common occurrence as a soil, groundwater, and surface water contaminant; and demonstration of carcinogenicity in animal bioassays (ATSDR 1989, EPA 1985). The Superfund Amendments and Reauthorization Act (SARA) to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) based clean-up goals on Applicable or Relevant and Appropriate Requirements (ARARs). In the case of TCE, EPA's Office of Solid Waste Management uses the only national regulatory standard currently in use, the MCL, as the ARAR.

The MCL published for TCE was 5 ppb (EPA, 1985). Various other EPA regions use and enforce other concentrations. For example, Region 9 has established a preliminary remediation guideline for tap water of 1.6 ppb. EPA will accept a range of one in one million to one in ten thousand as being acceptable in terms of excess cancer risk (above a background cancer rate of 1 in 3). The current EPA MCL and Region 9 guidance reflect the more stringent one in one million level. EPA could have chosen to use the less stringent limit and thereby allowed a cleanup level as high as 500 ppb. We shall see that changes in the cleanup goal approaching one to two orders of magnitude have significant cost implications for the clean up of groundwater.

TCE's Behavior in the Environment

TCE is a halogenated solvent characterized as a dense non-aqueous phase liquid (DNAPL) with a relatively low solubility in water and high vapor pressure. If spilled onto the ground surface or into surface water, it tends more readily to vaporize into the atmosphere than to be transported into the subsurface soil or to mix in the surface water (Vogel *et al.* 1987; ATSDR 1989; Russell *et al.* 1992). Approximately 60 percent of the TCE produced in the United States is believed to volatilize rapidly and enter the atmosphere, where it is subject to a variety of degradation processes (Vogel *et al.* 1987).

TCE contamination has been detected in the vadose zone and the saturated zone (Vogel *et al.* 1987). ATSDR (1989) reports that TCE was detected at 0.2 ppb in approximately 10 percent of 945 groundwater sources used for drinking water. Because of its relative insolubility and greater density (1.46 grams per milliliter [g/ml], Vogel *et al.* 1987), TCE that does not volatilize will tend to migrate rapidly into the vadose and saturated zones (Vogel *et al.* 1987; ATSDR 1989). As is true of other DNAPLs, the fraction of TCE that does not solubilize in the groundwater will continue to sink until it meets a confining layer (ATSDR 1989; Russell *et al.* 1992).

TCE is not rapidly biodegradable because of the number of chlorine constituents that it possesses (ATSDR 1989; Vogel *et al.* 1987). This low biological activity coupled with relatively slow abiotic degradation means that TCE does not transform rapidly into other chemicals. Vogel *et al.* (1987) indicate that TCE nevertheless will degrade both biotically and abiotically over time.

METHODS, ASSUMPTIONS, AND PROCEDURES

Groundwater Model And Cost Estimate Development

This section discusses the methodology used to develop the inputs for the groundwater models that were used to establish parameters for the cost estimation models as well as the method used to develop the cost estimates for each of the three different sizes of aquifers. An earlier report entitled "Groundwater Modeling to Support an Analysis of Remediation: Costs for the Removal of Trichloroethylene From Groundwater" (PRC 1997) provides more detail on the groundwater model development process. It is provided as an Appendix.

Development of Parameters for the Groundwater Model

The intention of this project was to determine the potential cost avoidance associated with changes in the cleanup goal for TCE. Modeling parameters for three different size aquifers (5, 25, and 50 acres in area) were developed to provide a range of possible cases to examine for the cost estimation. The first step in developing the models was to develop a conceptual model.

The conceptual model was formulated to organize all assumptions so that the groundwater flow system could be analyzed more readily. The conceptual model was simplified as much as possible; however, enough complexity was retained to simulate groundwater system behavior adequately for the intended purposes of modeling (Anderson and Woessner 1992). Those assumptions are listed below.

Assumptions Required for Use in Analytical Models

- The aquifer is homogeneous, isotropic, and infinite in areal extent.
- Groundwater flow is horizontal, unidirectional, and at steady state.
- The size of the plume equals 5, 25 or 50 acres. Additional plume characteristics are provided in Table 1.

Assumptions Based on Assumed Field Data

- The hydraulic conductivity equals 100 feet per day (ft/d).
- The saturated thickness of the aquifer equals 50 ft.
- The transmissivity equals 5,000 ft/d.
- The magnitude of the hydraulic gradient equals 0.001.

TABLE 1. TCE PLUME CHARACTERISTICS

Plume Size (acres)	Length of Line Source (feet)	Maximum Width (feet)	Maximum Length (feet)	Plume Length to Width Ratio (unitless)	Approximate Time of Source Activity[a] (years)
5	300	300	800	2.70	5.5
25	400	800	1,800	2.25	12.3
50	400	1,000	2,700	2.70	18.5

Notes:

[a] Source activity describes the amount of time the source actively contributed contaminant mass to the aquifer. Plume concentration is assumed to be uniform and equal to 200 ppb.

Assumptions Based on Assumed Field Data (Cont.)

- The hydraulic gradient direction is east.
- The aquifer porosity equals 0.25 (unitless).
- The groundwater seepage velocity is 0.4 ft/d, or about 146 feet per year. This estimate is based on an average hydraulic conductivity of 100 ft/d, a hydraulic gradient of 0.001, and an effective porosity of 0.25, using a variation of Darcy's Law (Fetter 1980).
- The bulk density of the aquifer is equal to 1.7 grams per cubic centimeter (g/cm^3).
- The longitudinal/dispersivity equals 50, 25, or 10 feet dependent on the size of the plume (Gelhar 1986).
- The transverse dispersivity varies among 5, 2.5 and 1 feet, dependent on the size of the plume (Gelhar 1986).
- The total organic carbon (TOC) content of the aquifer equals 1.0, 0.10 or 0.01 percent, according to whether the adsorption rate is assumed to be high, moderate, or low (Olsen and Davis 1990).

Chemical-Specific Assumptions

- The concentration of TCE within the plume is spatially uniform and equals 200 ppb.
- The log of the organic carbon partition coefficient (log k_{oc}) for TCE is 2.1 liters per kilogram (L/kg) (EPA 1990).
- The retardation coefficient for TCE equals 1.1, 1.9 or 9.6 (unitless), and is a function of the assumed total organic carbon content.
- The source activity has ended or the source of contamination of groundwater has

been contained, and any remaining dissolved contamination migrates down gradient as a single slug.

- The rate of disappearance of TCE in groundwater by bio-degradation, volatilization, or transformation is insignificant.

The information presented above has been incorporated into the site conceptual model and forms the basis for all groundwater modeling for this report.

The Well Head Protection Area (WHPA) model (Blandford and Huyakorn 1991) was selected to simulate capture zones associated with pump-and-treat remedial systems. The analytical function-driven version of the model Random-Walk (Prickett *et al.*, 1981) was selected to simulate the migration of contaminants in groundwater and the progress of remediation. The WHPA model and the Random-Walk model are described in more detail in the Appendix.

Selection and Development of the Cost Estimation Model and Parameters

Version 3.2 of the Remedial Action Cost Engineering and Requirements (RACER) System was used to develop the cost estimates discussed in this report. RACER is an Air Force-supported cost estimating system that is routinely used by installation staff of the Military Services to develop engineering-level cost estimates for on-going remediation projects. RACER also has been used by the Office of the Deputy Under Secretary of Defense for Environmental Security (ODUSD[ES]) to develop program-level estimates of the cost of completing cleanup at all installations for which DOD is responsible.

Carbon adsorption (using granular activated carbon [GAC]) of the groundwater was selected as the technology of choice for removal of TCE. It is identified in EPA's Remedial Technology Screening Matrix (EPA 1995) as one of the technologies of choice for remediating groundwater contaminated with halogenated hydrocarbons. The technology also commonly is used at military installations throughout the U.S.

When developing high-level cost estimates, a number of assumptions must be made. Those assumptions affect the manner in which the final cost estimate is developed. They can be broken

down into assumptions about:

- The behavior of the aquifer and the contaminant of concern in the aquifer;
- The type of remedial approach that will be used;
- The location of the remedial activity; and
- The contingencies, allowances, and profit for contractors.

The first two points above have an effect on the length of time that operations and maintenance activities will be performed for each of the cases and the latter two points have an effect on the overall amount of each cost estimate.

The variables related to the aquifer that affect the cost of each scenario are the size of the aquifer, the cleanup level used for the case, and the adsorptivity of the soil matrix. Those factors are discussed briefly above and in more detail in the Appendix. These variables in turn affect the aggregate pumping rate used (which is based on the number of wells and the individual pumping rate for each well). Combined, the variables control the length of time that an aquifer will be pumped.

The location of the remedial activity and allowances and profits for contractors are RACER variables that do not change across the scenarios. The RACER model allows for changes in costs to account for differences in the cost of labor and materials in different parts of the country. For this study, Atlanta, Georgia was selected as the location for all remediation activities because its geographic weighting factor for costs is 1. Contractor contingencies, allowances, and profit can have a significant effect on overall costs. For all scenarios a factor of 10 percent each was used for both contingency and project management. RACER default values were used for other allowances and contractor profit.

Using the approach discussed above a separate RACER model run was set up for each scenario. The different periods of O&M time and the different number of wells and aggregate pumping rates for each scenario provided the major inputs that were used by the model to generate costs for:

- Well construction;
- O&M of the well system;
- O&M of the GAC system;
- Sampling and analysis; and
- Discharge to the publicly operated treatment works (POTW).

The cost estimate for well construction was calculated by the model based on the thickness of the aquifer (a screened length of 50 feet) and a depth to the aquifer of 25 feet. The number of wells was determined from the aquifer characteristics discussed above. The estimated cost of O&M of the well system was determined by the model based on the number of wells and the amount of time necessary to pump the aquifer clean. The estimated cost of installing the GAC system was based on the use of a replaceable cartridge system. The model calculated the O&M cost in light of the installed system and the length of time the wells were to operate. The estimated cost of sampling and analysis was based on an assumption of quarterly sampling for the first five years followed by yearly sampling for the remaining period of O&M. Discharge to the POTW was based on the aggregate pumping rate over the O&M period. The RACER default fee, $1.50 per kilogallon, was used.

After each scenario was run, a Project Summary Report was generated from the report formats available in RACER. The report allowed the determination of the total "loaded" cost of each scenario, the portion of that cost that represented capital expenditures and the portion of that cost that represented O&M operations.

In order to develop an estimate of the total cost to remediate TCE in groundwater, data from the Restoration Management Information System (RMIS) was used to determine the total number of sites where TCE was the main driver in remediation or the only contaminant (353 sites). The cost for each scenario then was multiplied by the number of sites identified. This value is used in discussions about the magnitude of total costs.

RESULTS AND DISCUSSION

This section presents and discusses the results of the cost modeling. The first section will analyze the costs generated by RACER. The second section will discuss the differences among costs attributable to the cleanup endpoint, aquifer size, and the retardation coefficient. The second section also will discuss the overall implications, in terms of cost, of application of the 100 ppb cleanup level as opposed to the current 5 ppb cleanup level.

It is important to realize that the aquifer characteristics chosen for the model may not be completely representative of the "real world." While we believe that the size of the aquifers and the range of carbon adsorption (retardation) coefficients are reasonable estimations for aquifers in DOD's inventory, we believe that the starting concentration limit of 200 ppb assumed for our model is likely to be lower than would be found in the "real world." This assumption is based on the fact that few if any of the DOD sites developed as a result of a one time spill event, and some are likely to still have sources releasing to the aquifer. In addition, we have assumed source removal as part of our model parameters. If the average concentration is, in fact, higher than the 200 ppb level used for this project and the sources have not been removed, then the average length of time (and therefore the average cost) will be higher.

It is also interesting to note the relatively small absolute mass of contaminant which bring about the 200 ppb average concentration. The five acre plume has a total of 33.92 pounds (a gallon of TCE weighs approximately 11.7 pounds); the 25 acre plume has 169.6 pounds; and the 50 acre plume has a 339.2 pound mass of TCE. The cost implications associated with these masses will be discussed below.

The results of the exercise are unsurprising. The overall cost to remediate to the 5 ppb cleanup level is, in all cases, higher for a given aquifer size or soil matrix adsorption level than the cost to achieve a less stringent standard. Also unsurprisingly, the cost to remediate the groundwater increases as adsorption increases.

Analysis of Cost Components

In any remediation program, there are three major components of cost: capital costs associated with the installation of various pieces of cleanup equipment, the placement of wells, and the excavation of soil; O&M costs, associated with the long-term management of a site, encompassing costs for operation of pump-and-treat systems, continued sampling of groundwater, maintenance of caps or fences; and the costs of allowances, profit, and overhead expenses associated with any engineering activity. Since the same percentage was used in all cases for allowances, profit, and overheads they will not be discussed as a separate factor.

Capital costs did not play a significant role in the overall costs of remediation. Capital costs averaged 8.1 percent of the total cost, with a range of from 1.4 to 19.2 percent of total cost. Capital costs were a much larger fraction of total cost for the small (five acre) aquifer because the O&M periods for the cases of this aquifer are far shorter, on average, than for either of the other two aquifer sizes.

Operations and Maintenance costs are by far the most significant component of the total cost. O&M costs increase as the amount of time a pump-and-treat system operates increases. The average contribution of O&M cost represented 59.7 percent of the total cost. It ranged from 47.3 to 68.2 percent. The difference between the sum of the capital and O&M averages set forth above represents the costs of allowances, profit, and overhead and expenses.

The capital costs contribution to the overall cost tend to decrease with the increasing size of the aquifers while O&M costs tend to increase. The mean percentage contribution of O&M costs are, on average, more than seven times greater than capital costs. This is a result of the fact that capital costs typically are incurred only once and O&M costs, which include replacement of equipment, recur over time.

Results of the RACER Cost Estimation Runs

Table 2 presents the cost estimate data generated for each case. The range of costs for the conditions modeled was $410,400 to $16,437,445, representing the smallest aquifer case, with

the lowest soil adsorptivity, and the largest aquifer case, with the highest adsorptivity. For each aquifer and cleanup level the step from the medium level of adsorptivity to the high level always resulted in the largest increase in cost. This suggests that the higher the percent organic matter in the aquifer (which, in part, controls adsorptivity) the more expensive the cleanup will be. Using mean costs (the bottom line in Table 2) the cost avoidance between the 5 ppb and the 50 ppb or 100 ppb endpoints is $822,074 (19 percent) or $1,251,542 (28 percent), respectively. Clearly, the differences in the cost estimates are significant in terms of dollar value. Use of 100 ppb as the cleanup endpoint results in a nearly 30 percent lower mean cleanup cost. Use of this less stringent cleanup level could contribute to a significant savings in remediation costs for these sites for use in other projects. The estimate presented here is likely to be lower than what will actually be seen for a variety of reasons that will be discussed later.

TABLE 2. SUMMARY OF TOTAL COST FOR EACH SCENARIO

Size / Retardation Rate	5 ppb Endpoint Cost	50 ppb EndpointCost (% Change from 5 ppb)	100 ppb EndpointCost (% Change from 5 ppb)
5 Acre / Low	$590,550	$467,708 (21)	$410,400 (31)
5 Acre / Medium	$754,794	$630,193 (17)	$570,302 (24)
5 Acre / High	$2,879,332	$ 2,199,086 (24)	$1,885,003 (35)
25 Acre / Low	$1,181,549	$1,108,503 (6)	$1,033,742 (13)
25 Acre / Medium	$2,111,395	$1,690,588 (20)	$1,469,813 (30)
25 Acre / High	$8,934,700	$6,530,203 (27)	$6,183,340 (31)
50 Acre / Low	$2,664,486	$2,053,168 (23)	$1,606,994 (40)
50 Acre / Medium	$3,987,883	$3,070,909 (23)	$2,348,366 (41)
50 Acre / High	$16,437,445	$14,392,216 (12)	$12,769,401 (22)
Mean Cost	$4,393,471	$3,571,397 (19)	$3,141,929 (28)

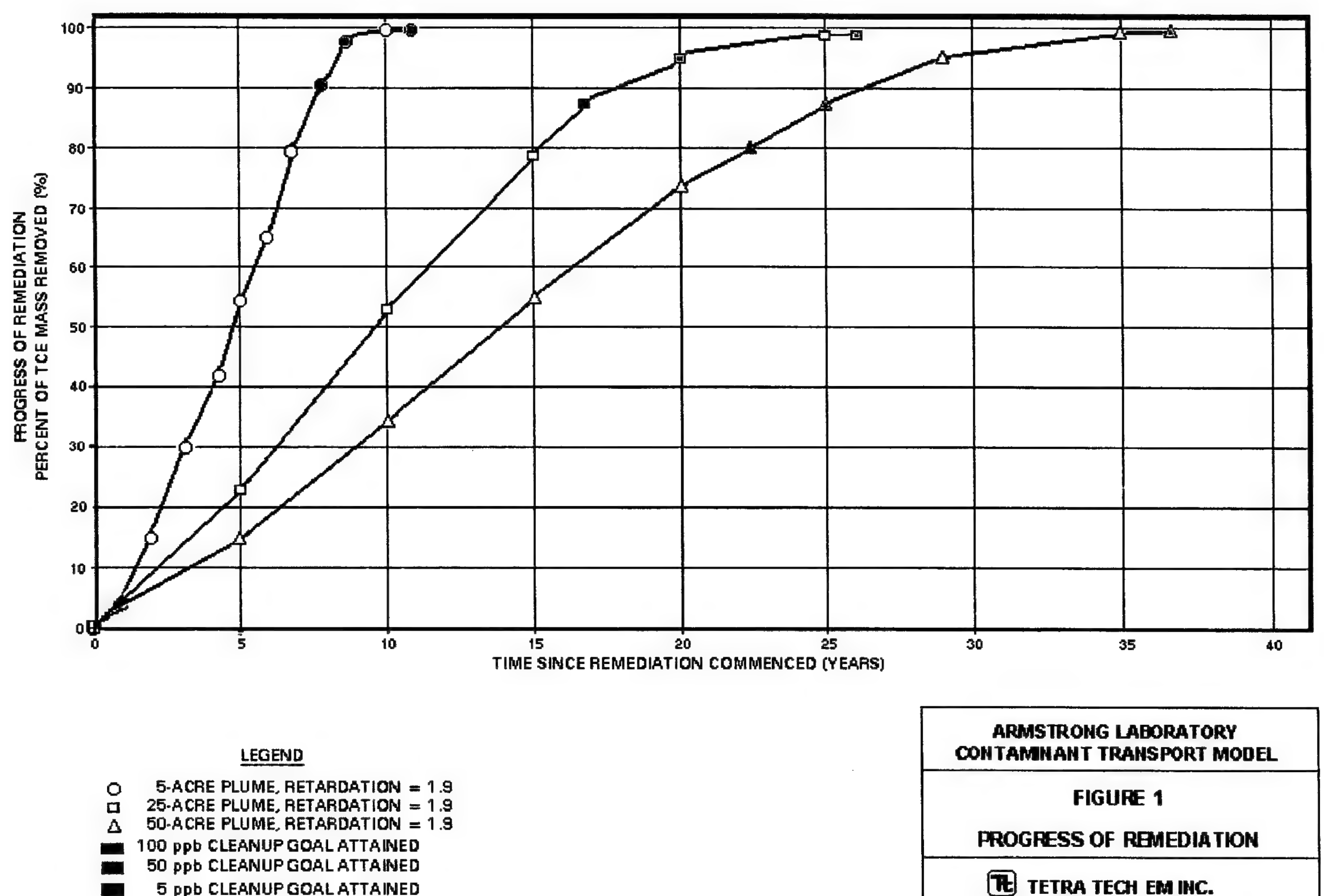
Using the assumptions of 25 acre plumes, with medium absorptivity, it would cost (in 1996 dollars) $1.551 billion if these 353 sites were to be cleaned up to the 5 ppb endpoint. If the 100 ppb endpoint were used, the cost would be $1.110 billion. The potential cost savings the could be effected by use of the less stringent cleanup endpoint are on the order of $441 million.

Another way to evaluate the cost is to consider the amount spent to remove the total mass of contaminant over time. Figure 1 is a schematic representation of the efficiency of removal of TCE for each of the aquifer sizes assuming moderate adsorptivity. The y-axis is the percentage of mass removed and the x-axis is time. The curves represent the efficiency of removal of the total amount of contamination and are approximately the same shape for each plume size with the number of years to reach the cleanup endpoint changing based on whether the endpoint is 5, 50, or 100 ppb.

The range of time spent in reaching cleanup for each of the plume sizes was as little as 7.5 years, for the 5-acre plume at the 100 ppb cleanup endpoint, to 37 years for the 50-acre plume at the 5 ppb cleanup endpoint. For each of the plume sizes, the range of time between reaching the 5 ppb and 100 ppb cleanup endpoints varies. For the 5-acre plume size the range is 4.5 years; it increases to 9 years for the 25-acre plume; and is largest for the 50-acre plume at 14.5 years. Below is a discussion of the behavior of the line describing the 25 acre plume.

The figure indicates that 17 years of remediation is required to remove 87 percent (or 147 lbs) of the contaminant mass originally present in the aquifer. This reduces the maximum observed concentration in the aquifer from 200 ppb to 100 ppb -- a factor of 50 percent. After the 17 year point, a proportionally smaller mass of contamination is removed, but the maximum observed concentration in the aquifer decreases significantly. For example, after 26 years of remediation, 99 percent of the contaminant mass is removed and the maximum observed concentration of contaminants in the aquifer decreases to 5 ppb. What this means in absolute terms is that it will take nine more years to remove an additional 20.3 pounds of contaminant when cleaning up to the 5 ppb endpoint in this scenario.

The observed mass removal rate and concentration primarily are controlled by advection and dispersion. The contaminant plume passes through the aquifer as a slug with an assumed uniform concentration of 200 ppb . The concentration within the contaminant plume remains fairly constant, except for the down gradient end which experiences a spreading out of the concentration profile as a result of dispersion. Since the extraction wells are located on the



ARMSTRONG LABORATORY
CONTAMINANT TRANSPORT MODEL

FIGURE 1

PROGRESS OF REMEDIATION

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farthest down gradient edge of the plume, the concentration of contaminants in the upgradient areas of the plume are unaffected and remain relatively constant, even though the total mass of contaminants in the aquifer is significantly reduced. While the contaminant plume is moving during the process of remediation, the leading edge of the plume disperses and decreases in concentration. During the latter stages of remediation (after 17 years in this particular case) this impact of the dispersion front plays a more important role and the maximum observed concentration decreases significantly during years 17 through 26.

Table 3 relates the cost data from Table 2 with the percentage removal of mass data in Figure 1 for the 25 acre medium retardation case. A total of $1.47 million was spent to remove the first 87 percent (or 147 lbs) of the total mass of TCE contaminant. Removal of 99 percent (an additional 20.3 lbs of TCE) entailed a cost of $2.11 million. Comparing the unit costs (cost per percentage point of mass removed) shows that the 87 percent of mass removed achieves the 100 ppb cleanup endpoint at a cost of $16,896 per percentage point, while it is necessary to remove 99 percent of the mass to achieve the 5 ppb cleanup endpoint at a cost of $21,327 per percentage point. These figures represent the average cost over the entire time period to reach the particular endpoint. While average costs provide information on the behavior of the system over its lifetime, the marginal cost provides information on the magnitude of cost (which is entirely O&M related) for the additional cleanup. The marginal cost is the absolute difference between reaching the 5 ppb endpoint versus the 100 ppb endpoint. The marginal cost difference between the two endpoints is $641,582, yielding a unit cost of $53,333 per percentage point for the final 12 percent of mass removed. Another way to evaluate this difference is from the viewpoint of the cost, per pound, to remove the additional 20.3 pounds of TCE. This would yield a unit cost, per pound of TCE removed, of $31,605. This clearly demonstrates that removing the last few percent of the mass of TCE from a system is increasingly less cost efficient both in terms of average and marginal costs.

Looking at the total cost in terms of cost per pound removed, also shows significant differences. Over the life of a project, cleanup to the 100 ppb endpoint is 21 percent less expensive than cleanup to the 5 ppb endpoint. Larger absolute masses of TCE, whether as a result of larger area

TABLE 3. COSTS FOR REMOVAL OF DIFFERENT PERCENTAGES OF MASS
(25 Acre Medium Retardation Case)

Cost ($)	Mass Removed (%)	Absolute Mass Removed (lbs)	Cleanup Endpoint (ppb)	Average Cost Per Percent Mass Removed ($)	Average Cost Per Pound Mass Removed ($)
1,469,813	87	147.6	100	16,896	9,958
2,111,395	99	167.9	5	21,327	12,575

extent of contamination, higher average concentration, or some other factor will magnify this difference in terms of the total cost to clean up individual sites.

CONCLUSION

The savings of $441 million represents a conservative estimate and probably represents the minimum savings that could be expected for a change in the MCL from 5 ppb to 100 ppb. There are a variety of reasons for this related to the assumptions made in the model. While the model used here was developed to provide as much realism as possible, every assumption made for its operation has the potential to make it less descriptive than the "real world." A discussion of how some of these assumptions effect the cost is below.

The Source Removal Assumption: In developing the model parameters, it was assumed that the contamination source had been removed in order to minimize model complexity. When evaluating real sites it is much more common to have a continuing source in place, either because its precise location can not be determined or because source removal has not yet been initiated. In either case, this leads to longer pump and treat periods because a source of TCE continues to contribute to contamination. The longer pump and treat periods will in turn increase the treatment costs.

The Homogeneous Plume Concentration Assumption: This assumption was made to minimize model complexity. Assuming that there is a concentration gradient also leads to longer pump and treat periods and also may change the well layout assumptions leading to more wells pumping. These changes also would increase costs.

Plume Size and Retardation Rate Assumptions: The plume sizes and retardation rates selected for modeling represent a reasonable range of sizes and retardation rates for TCE plumes. However, no information on actual plume size or retardation rate distribution was available for the development of the average costs and a simple arithmetic mean of all the cases was used. This means that if the average plume size is greater than approximately 26.6 acres (the mean of the three plume sizes) and has higher than medium retardation, the average cost would increase because of the increased plume area (and thus volume) and higher retardation rate. Clearly, these parameters have the potential to significantly increase the cost.

Aquifer Thickness Assumption: The assumption used in the model was that the saturated thickness of the aquifer was 50 feet and that it started at a depth of 25 feet below ground surface. Should the aquifer be thicker or start deeper, then the well installation cost would increase as would the time period necessary for reaching the cleanup endpoint.

The 200 ppb Concentration Assumption: This assumption was used in the development of the model. Subsequent information indicates that as many as 35 percent of the sites may have TCE concentrations in excess of 500 ppb. This would significantly increase overall costs since concentration is one of the more important factors in determining the time it will take to reach the cleanup endpoint.

Next Steps: Subsequent papers should attempt to develop model parameters that are more realistic that use a *Monte Carlo* approach to the cost estimation outputs and provide an estimate of savings that would be more realistic. (The *Monte Carlo* approach would allow a larger universe to be used and provide a more rigorously statistical approach.) To evaluate more thoroughly the potential benefits of the various levels of cleanup proposed for the site against the respective costs for each level, it might be helpful to conduct a cost-benefit analysis of each option.

To conduct such an analysis, it would be necessary first to calculate the total costs associated

with each cleanup endpoint and determine the differences in the amounts of residual contamination that would result from the implementation of the various endpoints. The next step would be to attempt to identify and quantify costs that might result from failure to clean the site to the currently accepted cleanup level of 5 ppb. Such costs might include: 1) costs of loss of human life; 2) costs of health care for persons sickened by the residual contamination; 3) costs of loss of productivity (including lost wages) of persons or assets affected by residual contamination at the site; 4) costs of restitution for collateral damage to the environment; 5) costs of damage to personal property (including the loss of market value of properties located near the site) or costs associated with limits placed on the use of such property; 6) costs of payment for legal settlements for damages for third-party liability; 7) costs for maintenance or long-term care of contaminated properties; 8) and costs of lost tax revenues to federal, state, and local governments for persons and property affected adversely by the residual contamination.

Comparison of costs expended to achieve each level of cleanup, with the benefits (or costs avoided) of achieving that level, can produce quantified data on net costs for each cleanup option at the site and assist in determining the economic feasibility of those options.

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APPENDIX

GROUNDWATER MODELING TO SUPPORT AN ANALYSIS OF REMEDIATION COSTS FOR THE REMOVAL OF TRICHLOROETHYLENE FROM GROUNDWATER

GROUNDWATER MODELING TO SUPPORT AN ANALYSIS OF REMEDIATION COSTS FOR THE REMOVAL OF TRICHLOROETHYLENE FROM GROUNDWATER

INTRODUCTION

PRC Environmental Management, Inc. (PRC-EMI) is providing Armstrong Laboratory with program support that consists of developing cost estimates for remediating trichloroethylene (TCE) in groundwater. This groundwater modeling report satisfies the requirements outlined in Section 1.2.1 of the scope of work (SOW) issued by Armstrong Laboratory dated September 19, 1996. In this report, pump-and-treat alternatives for 27 scenarios were evaluated to determine the number of wells required, optimal discharge rates, and estimated time required to reach predetermined cleanup goals. The scenarios included three hypothetical TCE plumes, three assumed TCE adsorption rates (retardation coefficients), and three plume sizes.

The information on numbers of wells, pumping rates, and length of time until cleanup is complete is being used to parameterize the Remedial Action Cost Engineering Requirements (RACER) System to develop costs for remedial action under each of the 27 scenarios. The costs that are generated for each scenario's specific conditions will be used to provide a position for reducing the stringency of the current TCE cleanup requirement.

METHODS, ASSUMPTIONS, AND PROCEDURES

Modeling Approach

In response to the Armstrong Laboratory (AL) scope of work, a matrix of assumptions regarding plume size, cleanup goals, and rate of adsorption was developed and pre-approved for modeling and evaluation. In addition, standardized aquifer conditions were assumed for a hypothetical aquifer so that pump-and-treat alternatives would be evaluated in a manner that was unbiased, consistent, and reproducible. Plumes of TCE that were 5, 25, and 50 acres in size were initialized and pump-and-treat technology was simulated using a range of adsorption rates. The objective of modeling was to simulate contaminant migration and the progress of pump-and-treat remediation for 27 modeling scenarios. A summary of model simulations and corresponding model scenarios is provided in Figure 1.

PLUME SIZE / MODEL RUNS

5 ACRES

CLEANUP GOALS

ADSORPTION RATE	5 $\mu g/L$	50 $\mu g/L$	100 $\mu g/L$
LOW	RUN 1	RUN 2	RUN 3
MODERATE	RUN 4	RUN 5	RUN 6
HIGH	RUN 7	RUN 8	RUN 9

25 ACRES

CLEANUP GOALS

ADSORPTION RATE	5 $\mu g/L$	50 $\mu g/L$	100 $\mu g/L$
LOW	RUN 10	RUN 11	RUN 12
MODERATE	RUN 13	RUN 14	RUN 15
HIGH	RUN 16	RUN 17	RUN 18

50 ACRES

CLEANUP GOALS

ADSORPTION RATE	5 $\mu g/L$	50 $\mu g/L$	100 $\mu g/L$
LOW	RUN 19	RUN 20	RUN 21
MODERATE	RUN 22	RUN 23	RUN 24
HIGH	RUN 25	RUN 26	RUN 27

NOTE:
$\mu g/L$=MICROGRAMS PER LITER

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FIGURE 1

SUMMARY OF MODEL SIMULATIONS AND RUN IDENTIFICATION NUMBERS

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SUM-RUN.DWG - 01/03/97 - CFR - C01-052802

The approach to modeling was simplified to the maximum degree possible without compromising the stated objectives. In doing so, several smaller analytical models rather than one large numerical model were used to simulate (1) groundwater capture using pump-and-treat technology, (2) contaminant migration, and (3) the progress of remediation. The Well Head Protection Area (WHPA) model was selected to estimate the number of wells needed to effectively pump the aquifers. The WHPA is EPA-approved and is widely used in the public domain. It is distributed and supported by the International Groundwater Modeling Center (IGWMC) in Golden, Colorado. The Random-Walk model, that was used to simulate the behavior of the contaminant and determine time to cleanup is a public-domain computer model that simulates a large class of solute transport problems in groundwater. The Random-Walk code used in this investigation is distributed and supported by Thomas A. Prickett and Associates, Urbana, Illinois. Use of analytical models resulted in cost savings and rapid development of modeling scenarios, but should generally only be applied in answering specific questions (EPA 1992). The limitations of this approach are fully discussed in this report.

Site Conceptual Model

A conceptual model of the assumed site hydrogeology was formulated before a computer code was selected to simulate contaminant migration. A conceptual model describes the components of the groundwater flow system and is usually developed from regional, local, and site-specific data. Flow system components include parameters such as groundwater flow direction and gradient, aquifer thickness, and water transmitting properties. Development of a conceptual model is necessary before constructing a computerized groundwater flow or contaminant transport model.

All pump-and-treat alternatives were evaluated using standard aquifer conditions that were developed by PRC-EMI, and pre-approved by Armstrong Laboratory. The unconfined aquifer was assumed to be homogeneous and isotropic, consist of a sand and gravel material, and exhibit a porosity of 0.25, a hydraulic conductivity of 100 feet per day (ft/d), and a transmissivity of 5,000 square feet per day (ft/d). The bulk density of soil material was assumed to be 1.7 grams per cubic centimeter. A uniform hydraulic gradient of 0.001 was also assumed. These assumptions are discussed in more detail below. A cross section of the standard aquifer is

provided in Figure 2. It was assumed that the 50-foot thick, highly permeable sand and gravel aquifer is a preferential pathway for contaminants, and that an impermeable bedrock unit underlying the sand and gravel aquifer impedes the vertical flow of groundwater and TCE.

Assumptions Used For Modeling

The conceptual model was formulated to organize all assumptions so that the groundwater flow system could be analyzed more readily. The conceptual model was simplified as much as possible; however, enough complexity was retained to simulate groundwater system behavior adequately for the intended purposes of modeling (Anderson and Woessner 1992). The conceptual model was developed using data and information that was reviewed and approved by Armstrong Laboratory. Model assumptions are listed below.

Assumptions Required for Use in Analytical Models

·The aquifer is homogeneous, isotropic, and infinite in areal extent.

·Groundwater flow is horizontal, unidirectional, and at steady state.

·The size of the plume equals 5, 25 or 50 acres. Additional plume characteristics are provided in Table 1 of the main document (page 7).

Assumptions Based on Assumed Field Data

·The hydraulic conductivity equals 100.0 ft/d.

The saturated thickness of the aquifer equals 50 ft.

·The transmissivity equals 5,000 ft/d.

·The magnitude of the hydraulic gradient equals 0.001.

·The hydraulic gradient direction is east.

·The aquifer porosity equals 0.25 (unitless).

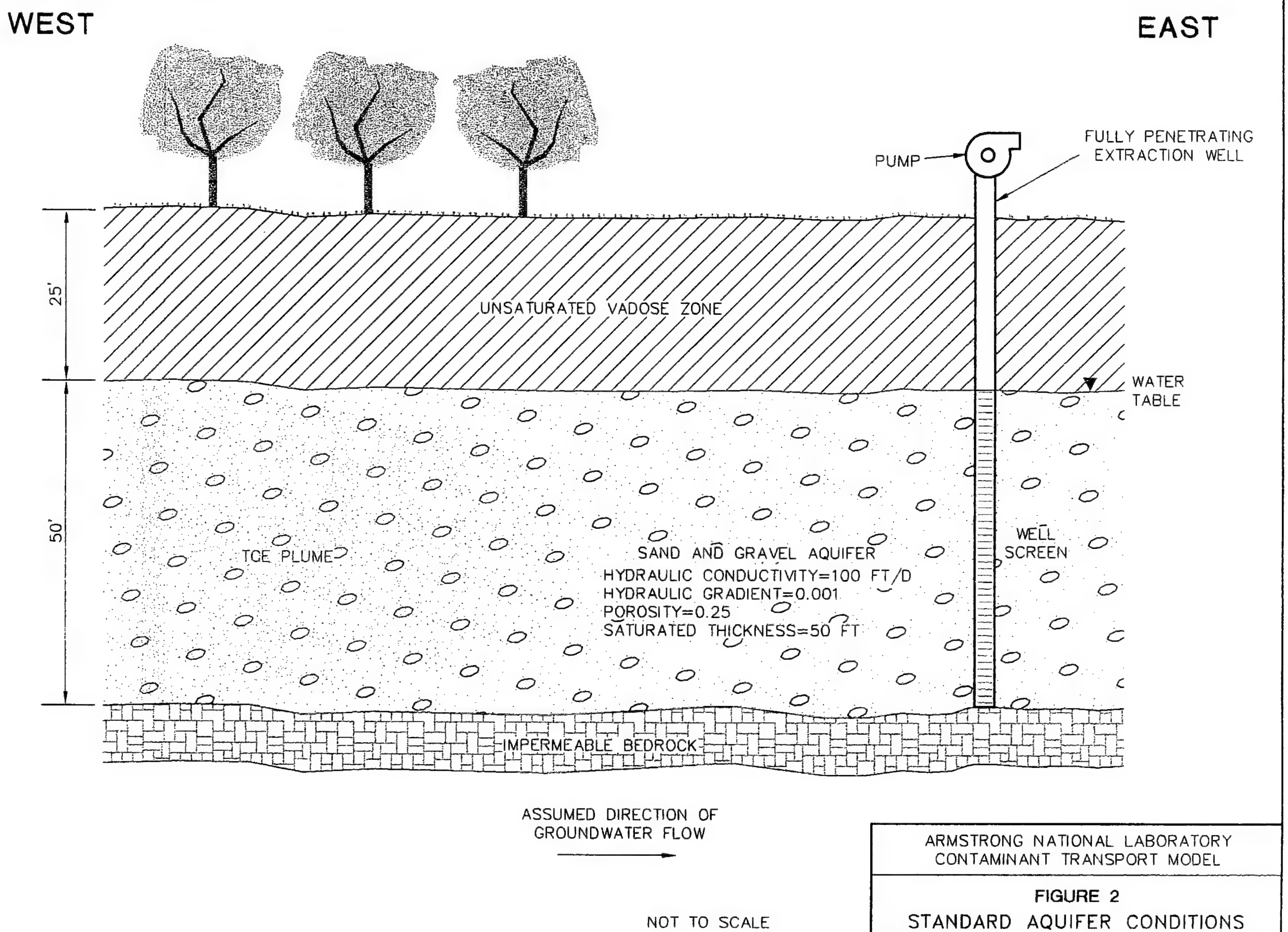

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FIGURE 2
STANDARD AQUIFER CONDITIONS

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·The groundwater seepage velocity is 0.4 ft/d, or about 146 feet per year. This estimate is based on an average hydraulic conductivity of 100 ft/d, a hydraulic gradient of 0.001, and an effective porosity of 0.25, using a variation of Darcy's Law (Fetter 1980).

$$Q = (K \times I) / n_e \tag{1}$$

where:

Q = seepage velocity, or pore water velocity (ft/d)
K = hydraulic conductivity (ft/d)
I = hydraulic gradient (ft/ft)
n_e = effective porosity (unitless)

·The bulk density of the aquifer is equal to 1.7 grams per cubic centimeter (g/cm^3).

·The longitudinal dispersivity equals 50, 25, or 10 feet dependent on the size of the plume (Gelhar 1986).

·The transverse dispersivity varies among 5, 2.5 and 1 feet, dependent on the size of the plume (Gelhar 1986).

·The total organic carbon (TOC) content of the aquifer equals 1.0, 0.10 or 0.01 percent, dependent on whether the adsorption rate is assumed to be high, moderate, or low (Olsen and Davis 1990).

Chemical-Specific Assumptions

·The concentration of TCE within the plume is spatially uniform and equals 200 micrograms per liter (µg/L).

·The log of the organic carbon partition coefficient (log K_{oc}) for TCE equals 2.1 liters per kilogram (L/kg) (EPA 1990).

·The retardation coefficient for TCE equals 1.1, 1.9 or 9.6 (unitless), and is a function of the assumed total organic carbon content.

·The source activity has ended or the source of contamination to groundwater has been contained, and any remaining dissolved contamination migrates down-gradient as a single slug.

·The rate of disappearance of TCE in groundwater due to biodegradation, volatilization, or transformation is insignificant.

The information presented above has been incorporated into the site conceptual model and forms the basis for all groundwater modeling. A summary of groundwater model input parameters is provided in Appendix Table 1.

APPENDIX TABLE 1. MODEL INPUT PARAMETERS

Parameter	Units	Model Value(s)	Reference
Hydraulic Conductivity	ft/d	100	Armstrong
Saturated Thickness	ft	50	Armstrong
Transmissivity	ft^2/d	5,000	Armstrong
Hydraulic Gradient	ft/ft	0.001	Armstrong
Porosity	NA	0.25	Armstrong
Bulk Density	g/cm^3	1.7	Olsen and Davis 1990
Longitudinal Dispersivity	ft	50 - 25 - 10	Gellhar 1986
Transverse Dispersivity	ft	5.0 - 2.5 - 1.0	Gellhar 1986
Log K_{oc}	ml/g	2.10	EPA 1990
TCE Partition Coefficient	ml/g	126	EPA 1990
Fraction of Organic Carbon	NA	0.01 - 0.001 - 0.0001	Olsen and Davis 1990
Contaminant of Concern	-	Trichloroethylene (TCE)	Armstrong
TCE Solubility	mg/L	1,000	EPA 1990

Notes:

ft	=	Feet
ft/ft	=	Foot per foot
ft/day	=	Feet per day
ft^2/d	=	Square feet per day
mg/L	=	Milligrams per liter
NA	=	Not Applicable
Armstrong	=	Armstrong Laboratory
g/cm^3	=	Grams per cubic centimeter
ml/g	=	Milliliters per gram

Description Of The Modeling Process

The process of modeling capture zones, simulating contaminant migration, and evaluating the progress of remediation using pump-and-treat technology is presented in Figure 3. Aquifer parameters presented in the Assumptions and Appendix Table 1 were input to the capture zone and contaminant transport models. A 4,000 ft by 2,000 ft model domain 40 nodes long by 20 nodes wide was constructed. Nodal spacing was set at 100 feet. Groundwater was assumed to flow from west to east at a hydraulic gradient of 0.001. Three TCE plumes as described Table 1 (page 7) were initialized as shown in Figures 4, 5, and 6 for the 5 acre, 25 acre, and 50 acre plumes, respectively.

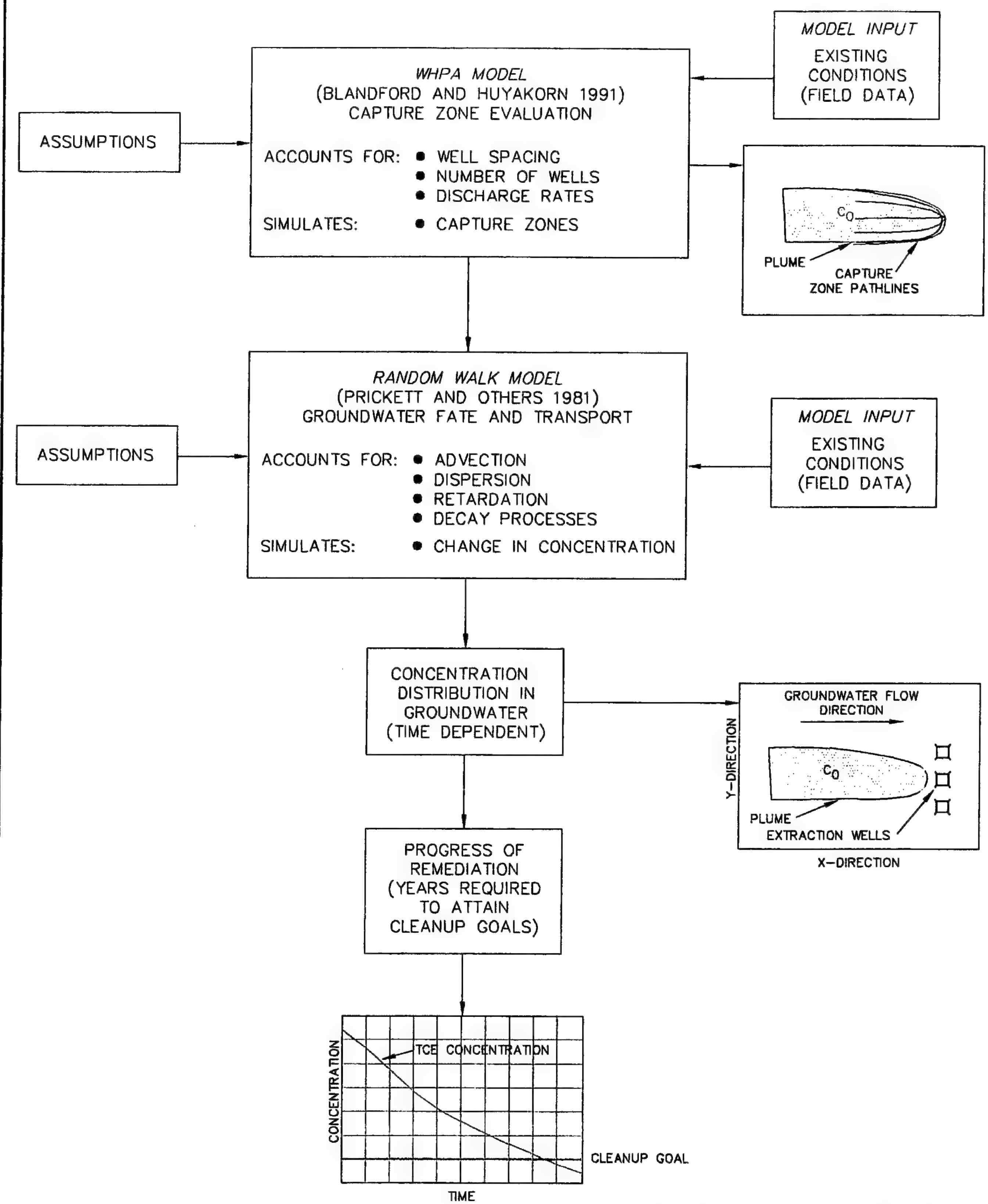

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FIGURE 3
SUMMARY OF MODEL PROCESS

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PROCESS.DWG - 12/27/96 - CFR - GIH-052802

TCE-PLUM.DWG - 12/27/96 - CFR - C01-052802

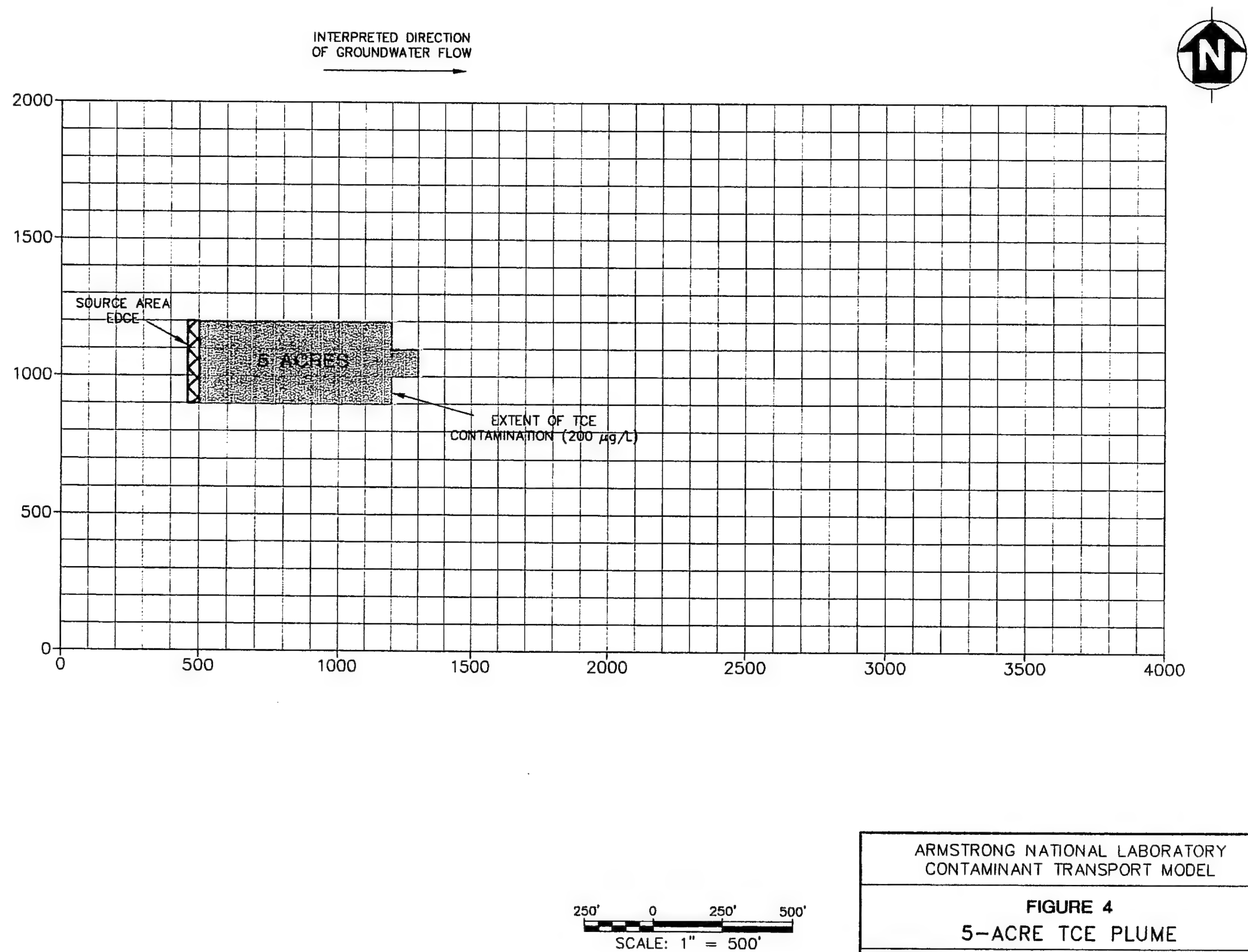

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FIGURE 4

5-ACRE TCE PLUME

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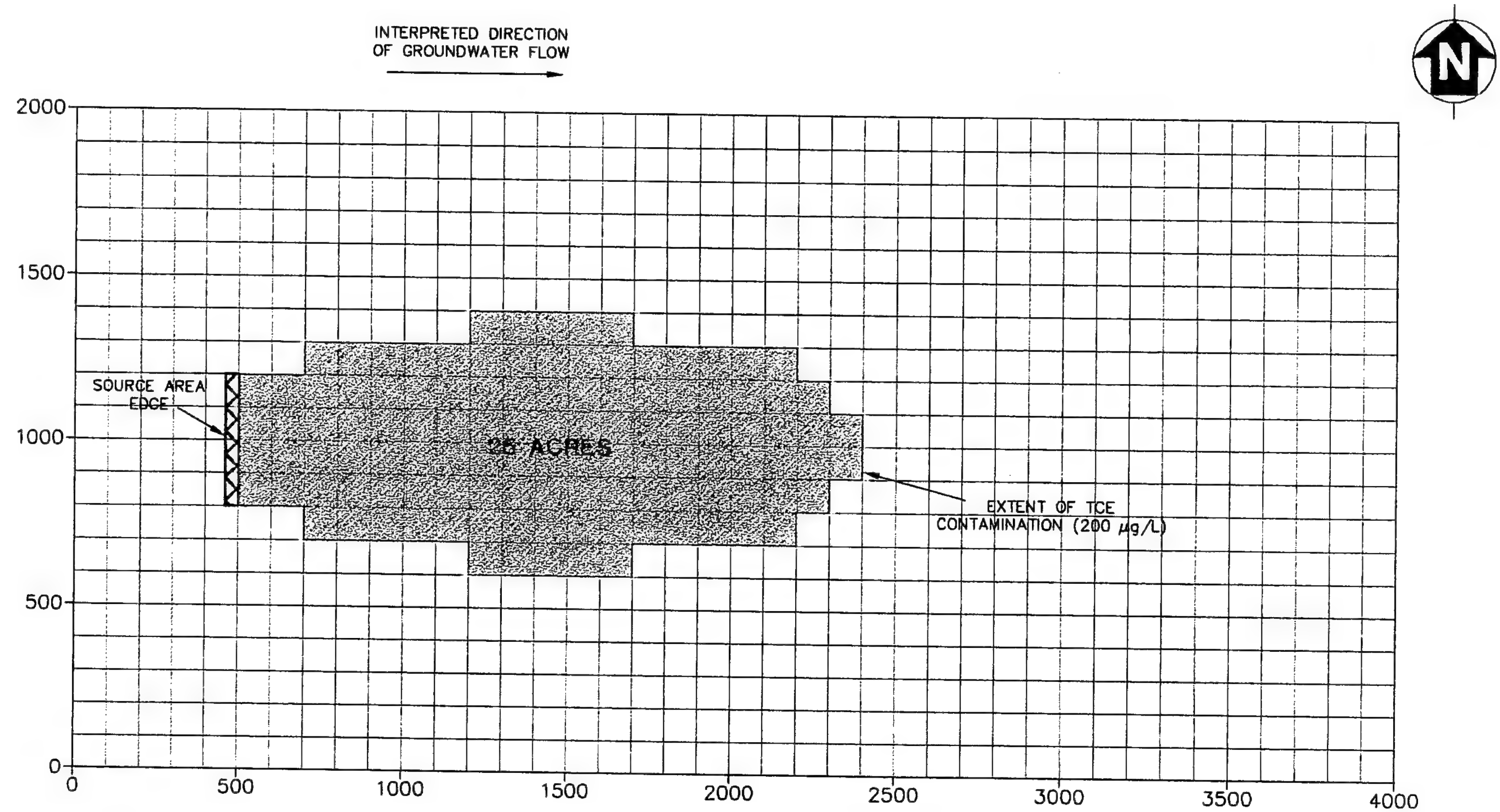

250' 0 250' 500'
SCALE: 1" = 500'

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FIGURE 5

25-ACRE TCE PLUME

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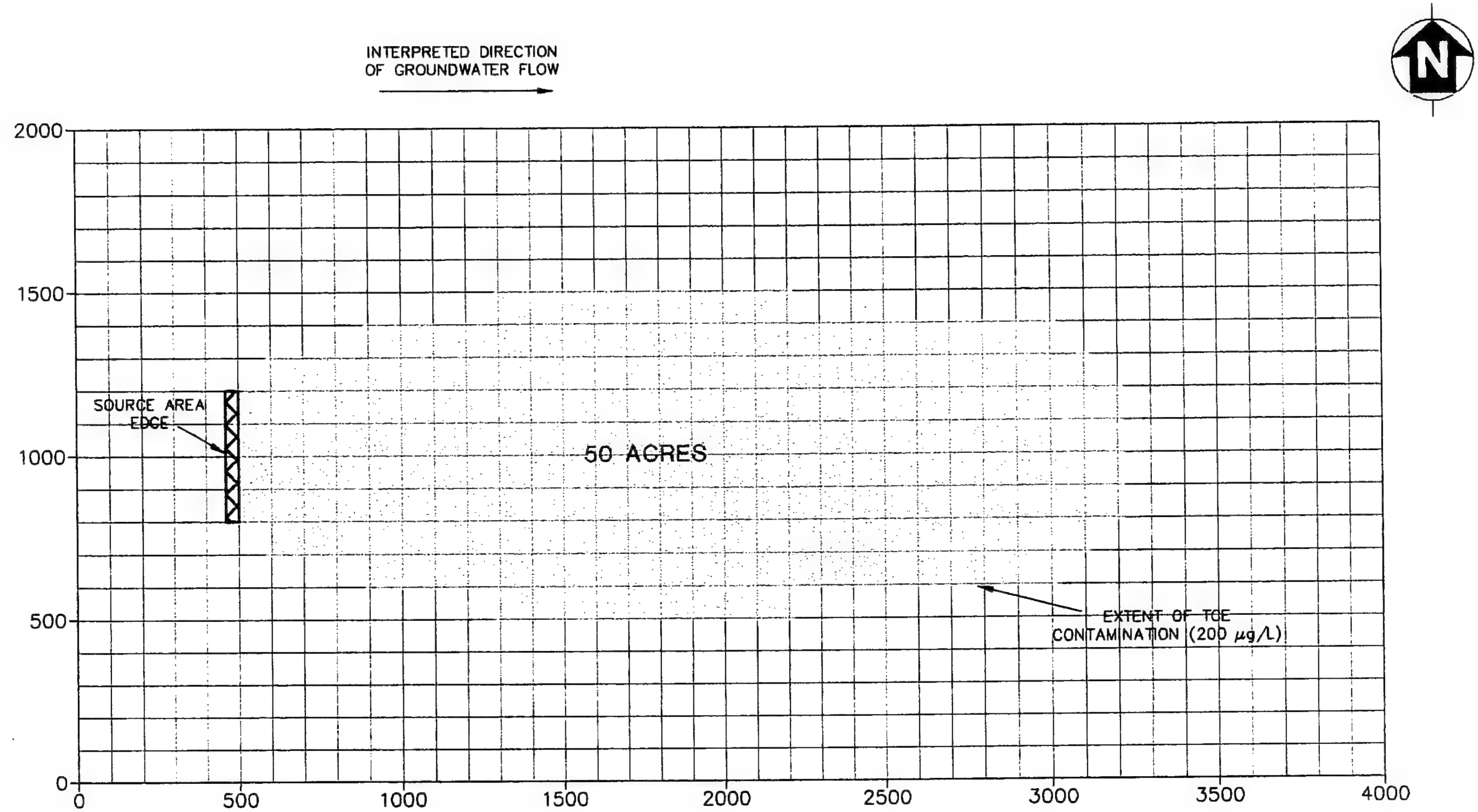

250' 0 250' 500'
SCALE: 1" = 500'

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FIGURE 6
50–ACRE TCE PLUME

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The WHPA model (Blandford and Huyakorn 1991) was selected to simulate capture zones associated with pump-and-treat remedial alternatives. The WHPA model is described below. The analytical function-driven version of the model Random-Walk (Prickett, *et al.* 1981) was selected to simulate the migration of contaminants in groundwater and the progress of remediation. The Random-Walk model is described below.

After calculating the extent of capture for each of the pump-and-treat scenarios, PRC-EMI simulated the bulk movement of contaminants in groundwater and the removal of contaminants over time. Simulated TCE concentrations were compared to the 100 µg/L, 50 µg/L and 5 µg/L cleanup goals. The simulations were terminated when the simulated concentrations of TCE in the aquifer decreased, and became equal to or less than the proposed cleanup goal.

Description Of The WHPA Model

The WHPA model is a semi-analytical program based on superposition of mathematical solutions for groundwater movement that would result from pumping extraction or injection wells in the presence of a regional hydraulic gradient. The WHPA model delineates capture zones associated with discharging extraction wells using a particle tracking technique. A particle is viewed as an individual molecule of water or molecule of a conservative tracer that moves through the aquifer coincident with the bulk movement of groundwater flow. Time-related capture zones are obtained by tracing the pathlines formed by a series of particles placed around the well bore of the pumping well. These particles are either forward- or reverse-tracked with time.

Description Of The Random-Walk Model

The model is capable of simulating the effects of advection, dispersion, decay, and retardation. The analytical function-driven version of this model simulates the concentration distribution of a contaminant in a homogeneous, isotropic aquifer. The Random-Walk model can also incorporate time-varying pumping or injection by wells and artificial recharge. Random-Walk calculates contaminant concentrations in extracted groundwater at simulated extraction wells. The solute transport portion of the computer model code is based on a particle-in-a-cell technique for advection and on a Random-Walk technique for dispersion.

RESULTS AND DISCUSSION

This section provides the results of the WHPA model runs and subsequent Random-Walk modeling to determine time to completion of the remedy based on the three final cleanup concentrations, three adsorption rates, and three plume sizes. The WHPA model was used essentially to develop the well pumping parameters and number of wells necessary to pump a given aquifer. The Random-Walk model was used to estimate the length of time it would take to clean up a given aquifer to a given cleanup level.

Results From The WHPA Model

Capture zone analyses were performed for the three plumes using the WHPA model. The number of wells, well locations, and discharge rates for all pumping wells was optimized through a series of computer simulations. The objective of the optimization process was to create a hydraulic barrier that captured 100 percent of the contaminant plume using the least number of wells and the lowest possible discharge rates. The optimized system results in the most efficient performance and lowest possible remediation costs. While additional wells located within the interior of the plume, and operated using a pulse-pumping technique, could reduce the total cleanup time, this type of system was not considered for this preliminary evaluation. PRC-EMI can evaluate the effects of pulse-pumping under a separate SOW.

Simulated capture zones for the three TCE plume scenarios are provided in Figures 7, 8, and 9. Modeling results in Figure 7 indicate that one well discharging at 12.5 gallons per minute (gpm) will contain the 5-acre plume. Figure 8 suggests that three wells discharging at 10 gpm each (total discharge rate of 30 gpm) would capture a 25-acre plume. Figure 9 indicates that three wells discharging at 18 gpm each (total discharge of 54 gpm) would capture the 50-acre plume. The information on the number of wells and pumping rate are being used to parameterize the RACER model for the development of costs. Once the optimized configuration for each pump-and-treat remedial system was determined, the system was simulated using Random-Walk, and the progress of remediation was evaluated by comparing concentrations of TCE in groundwater to proposed cleanup goals. The results of Random-Walk modeling are discussed below.

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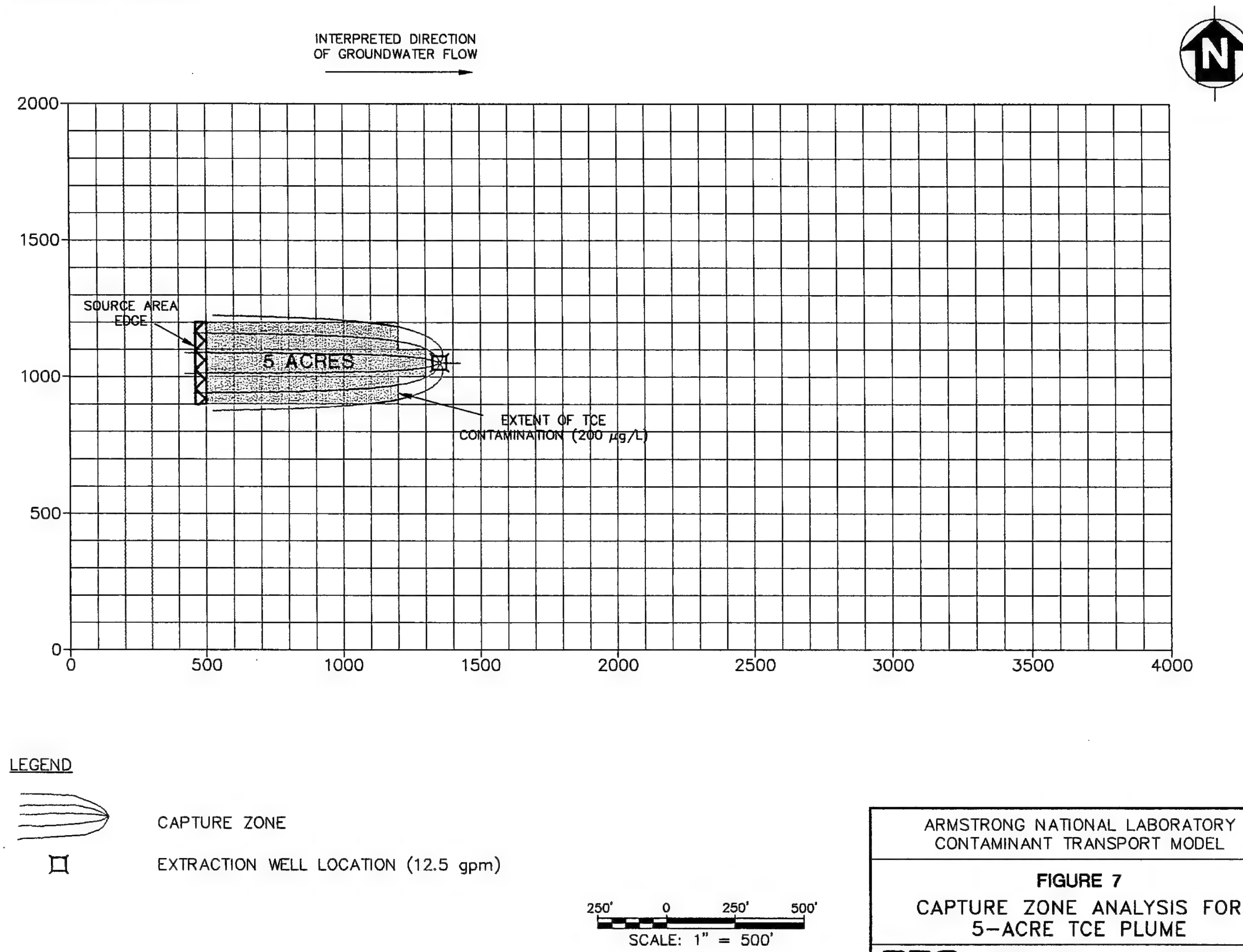

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FIGURE 7

CAPTURE ZONE ANALYSIS FOR
5-ACRE TCE PLUME

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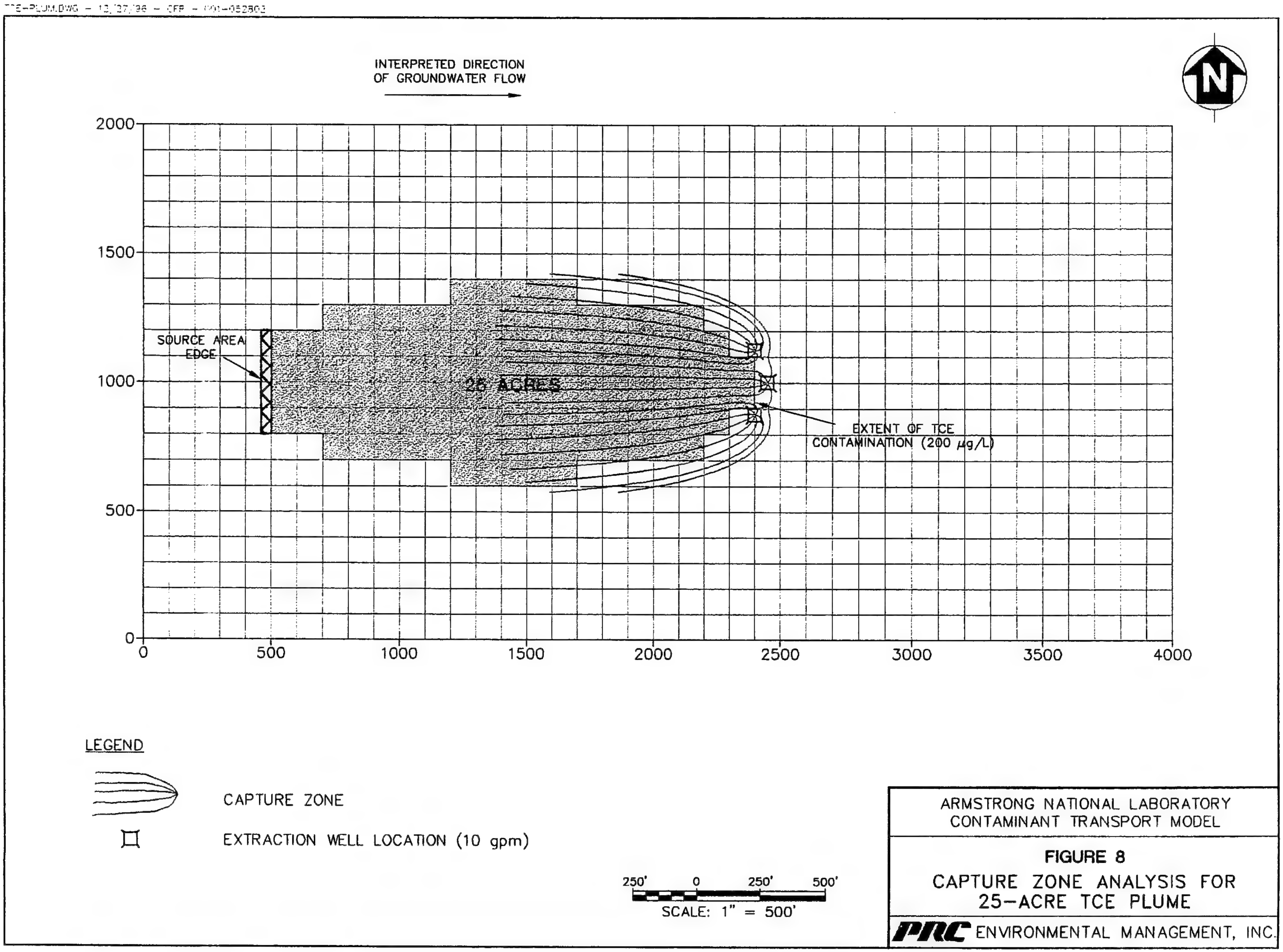

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FIGURE 8

CAPTURE ZONE ANALYSIS FOR 25-ACRE TCE PLUME

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TCE-PLUM.DWG - 01/06/97 - CFP - 001-052802

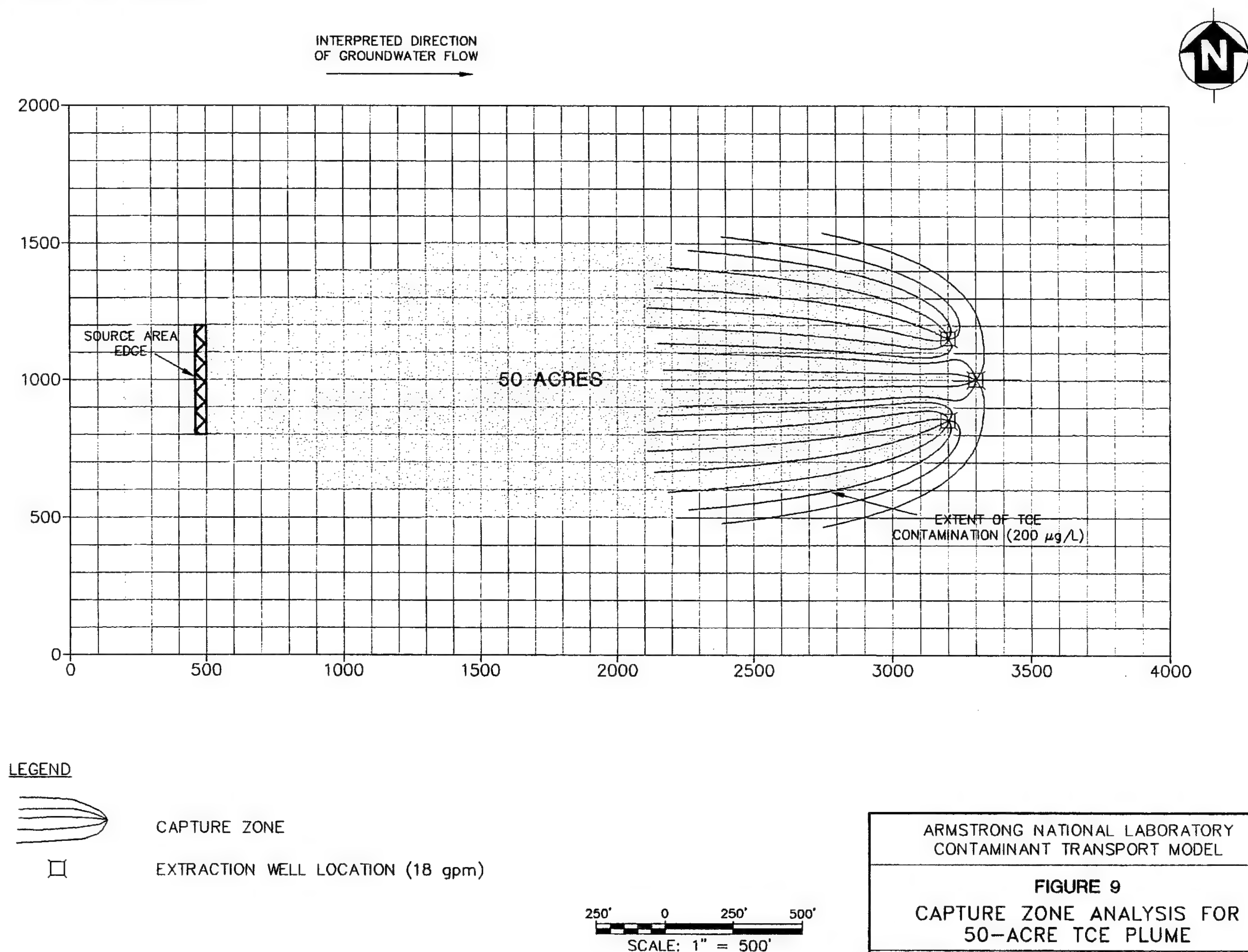

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FIGURE 9

CAPTURE ZONE ANALYSIS FOR
50-ACRE TCE PLUME

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Results From The Random-Walk Model

Random-Walk models were constructed for the 3 plume configurations (5, 25, and 50 acres), three adsorption rates (low, moderate, and high), and three cleanup goals (5, 50, and 100 µg/L), for a total of 27 model simulations. Low, moderate, and high adsorption rates corresponded to retardation coefficients of 1.1, 1.9, and 9.6, and were calculated using the assumed total organic carbon content of the soil matrix and an organic carbon partition coefficient for TCE from the literature. A summary of simulations for all initial conditions is presented in Figure 10. For each Random-Walk model, the initial concentration of TCE in the aquifer was set equal to 200 µg/L, as determined in the scope of work. The area of each TCE plume (5, 25, and 50 acres) was digitized to determine the total mass of contaminants in the plume. The available mass was then used to initialize the contaminant plumes and model input parameters for each of the Random-Walk models.

The initial model particle distributions for TCE are provided in Figures 4, 5, and 6. The initialized models required approximately 880 particles to simulate the 5-acre plume, 4,560 particles to simulate the 25-acre plume, and 8,720 particles to simulate the 50-acre plume. Each particle had an associated mass, which when diluted in a specified volume of aquifer represented a defined concentration of TCE. As TCE particles were captured by the simulated pump-and-treat system, the number of particles in the aquifer system decreased, and the corresponding concentration of TCE reflected this decrease accordingly. Contaminant fate and transport were simulated on an annual basis until specified cleanup goals were attained; at this point in the simulation the model execution was terminated.

The number of years required to reach cleanup goals for each of the model scenarios is summarized in Figure 10. Figure 10 suggests that a hypothetical 5-acre TCE plume could be remediated in 5 to 11 years for aquifers characterized by low to moderate rates of adsorption. A 25-acre TCE plume could be remediated in 11 to 26 years under similar aquifer conditions. A 50-acre plume could be remediated in 15 to 37 years. A much longer remediation time would be required to attain cleanup under all scenarios that assumed a high rate of adsorption (retardation coefficient equal to 9.6), suggesting that pump-and-treat remediation is not as practical.

PLUME SIZE

YEARS REQUIRED TO REACH INDICATED CLEANUP GOALS

5 ACRES

PUMPING CONDITIONS
ONE WELL DISCHARGING
AT 12.5 gpm;
TOTAL DISCHARGE=12.5 gpm

ADSORPTION RATE	CLEANUP GOALS 5 $\mu g/L$	50 $\mu g/L$	100 $\mu g/L$
R=1.1 LOW	7	6	5
R=1.9 MODERATE	11	9	8
R=9.6 HIGH	52	40	34

25 ACRES

PUMPING CONDITIONS
THREE WELL DISCHARGING
AT 10 gpm EACH;
TOTAL DISCHARGE=30 gpm

ADSORPTION RATE	CLEANUP GOALS 5 $\mu g/L$	50 $\mu g/L$	100 $\mu g/L$
R=1.1 LOW	13	12	11
R=1.9 MODERATE	26	20	17
R=9.6 HIGH	118	93	85

50 ACRES

PUMPING CONDITIONS
THREE WELL DISCHARGING
AT 18 gpm EACH;
TOTAL DISCHARGE=54 gpm

ADSORPTION RATE	CLEANUP GOALS 5 $\mu g/L$	50 $\mu g/L$	100 $\mu g/L$
R=1.1 LOW	24	18	15
R=1.9 MODERATE	37	28	23
R=9.6 HIGH	158	138	122

NOTES:
R=RETARDATION COEFFICIENT
gpm=GALLONS PER MINUTE
$\mu g/L$=MICROGRAMS PER LITER

ARMSTRONG NATIONAL LABORATORY
CONTAMINANT TRANSPORT MODEL

FIGURE 10

SUMMARY OF MODEL SIMULATION RESULTS

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Limitations Of The Models

The results of current modeling activities are adequate to satisfy the primary objectives of this report. Specifically, model results provide (1) optimized well locations and pumping rates, (2) a reasonable estimate of contaminant migration in a hypothetical aquifer, and (3) the relative time required to attain predetermined cleanup goals using pump-and-treat technology. Development of analytical transport models involved incorporation of numerous assumptions and simplifications, and may not be representative of a particular hazardous waste site that may be of interest to Armstrong Laboratory. In addition, not all potential physical or chemical processes that impact contaminant migration have been evaluated in this report. For example, the model does not account for the degradation of contaminants in groundwater or loss of contaminants through volatilization. Degradation and volatilization would result in a decrease in mass and lower concentrations of TCE in groundwater. Degradation could also result in an increase in the concentrations of contaminants that may potentially be more toxic than the original parent chemical. This investigation did not assess the impact of the more toxic products of degradation, such as vinyl chloride.

For this investigation no attempt was made to perform a classical groundwater flow or contaminant transport calibration, or to simulate historic source releases. Therefore, the type of modeling application described in this report is consistent with the characteristics of a "generic model" (Anderson and Woessner 1992). According to Anderson and Woessner (1992), generic models are used to analyze flow in simplified hydrogeologic systems, may be useful to help frame regulatory guidelines, and do not necessarily require calibration.

As site-specific information becomes available, the WHPA and Random-Walk models can be constructed and calibrated to simulate contaminant transport at selected locations more accurately. The models can also provide more realistic estimates for Armstrong Laboratory review and decision making.

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